Phenomenology of the U(1)′-extended MSSM

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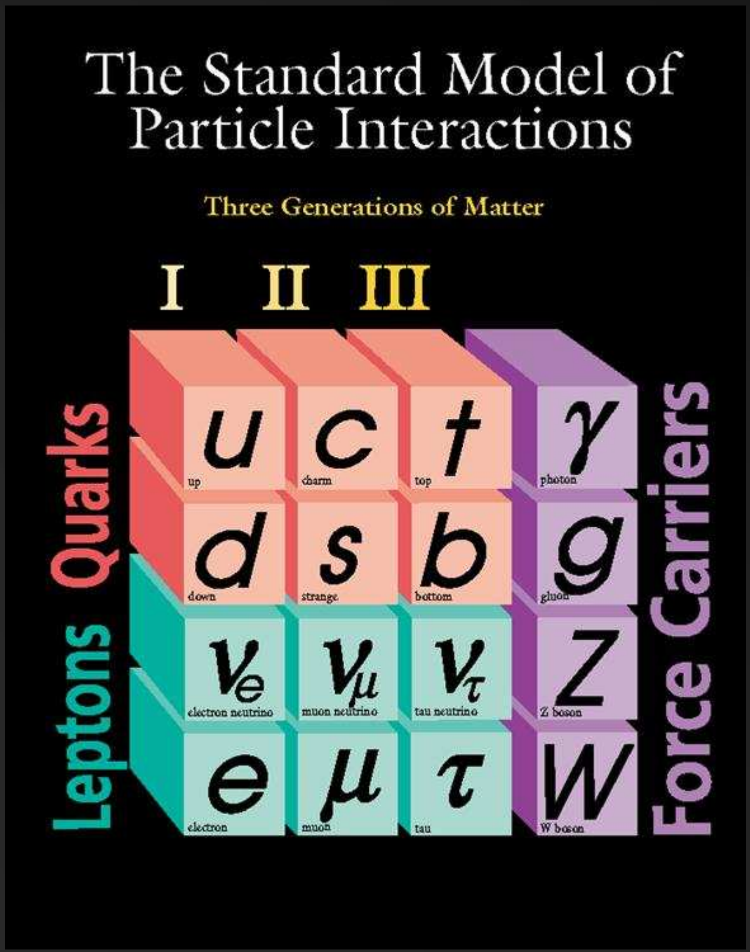
Outline

1. MSSM; success and limit
2. U(1)′-extended MSSM
3. TeV-scale U(1)′ gauge boson
4. Implications of U(1)′-extended MSSM
5. Summary

1. MSSM; success and limit

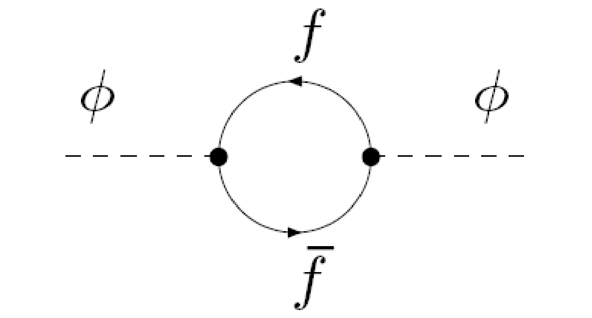
Standard Model (SM)



- Gauge group
  : $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Field contents
  : photon, gluon, Z, W
  (gauge bosons; force)
  quarks, leptons
  (fermions; matter)
  Higgs
  (scalar; mass-provider)

Gauge hierarchy problem of the SM

- Quantum loop correction (δm^2) of the Higgs scalar mass^2 by fermions ($m^2 = m_0^2 + \delta m^2$)



$$\delta m^2 = -2N_f\lambda_f^2 \int \frac{d^4k}{(2\pi)^4}\left(\frac{1}{k^2-m_f^2} + \frac{2m_f^2}{(k^2-m_f^2)^2}\right) \sim -O(\Lambda^2)$$

$O(\Lambda^4 / \Lambda^2)$

Λ : cut-off of integral (where SM looses effectiveness and New Physics is relevant)

- $m^2 = m_0^2 + \delta m^2 \sim m_0^2 - \Lambda^2$
  - Natural $\Lambda \sim$ Plank scale (10^{19} GeV) ; gravity
  - Natural m $\sim$ Electroweak scale (10^2 GeV) ; unitarity

- Fine-tuning of m_0 and Λ is required

  $(100)^2 = (10000000000000000000 + \alpha)^2 - (10000000000000000000)^2$

  : possible, but NOT natural (gauge hierarchy problem)

- We need a mechanism (or symmetry) to resolve this fine-tuning problem.

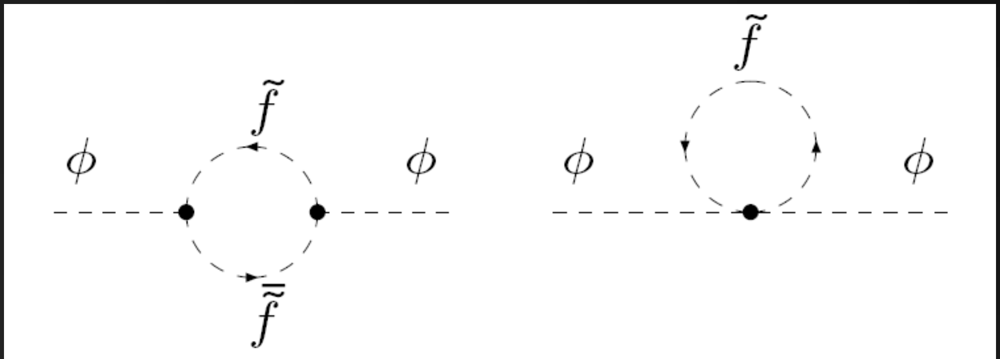
Supersymmetry (SUSY)

- Poincare group (symmetry)
  : spacetime symmetry of conventional field theory
- Supersymmetry
  : extension of Poincare sym by fermionic (spin ½) generators (unique extension of spacetime sym)

- SUSY relates boson (spin 0,1,⋯) to fermions (1/2,3/2,⋯)
  : For each fermion [boson], there is a boson [fermion] partner with same quantum number and mass.
  (SUSY doubles particle spectrum.)

SM fields	Superpartners
gauge bosons (photon, gluon, Z, W) (spin 1)	gaugino (photino, gluino, Zino, Wino) (spin ½)
quarks, leptons (spin ½)	squarks, sleptons (spin 0)
Higgs (spin 0)	Higgsino (spin ½)

Same quantum number except for spin (by ½)



$$\delta m^2 = 2N_f\lambda_f^2 \int \frac{d^4k}{(2\pi)^4}\left(\frac{1}{k^2-m_f^2}+\frac{2m_f^2}{(k^2-m_f^2)^2}\right) \sim O(\Lambda^2)$$

The bosonic loop ($\delta m^2 \sim \Lambda^2$) contribution exactly cancels the fermionic loop ($\delta m^2 \sim -\Lambda^2$) contribution.

(SUSY resolves the gauge hierarchy problem of SM)

Soft SUSY breaking

- Superpartners with the same mass were not discovered
  : SUSY should be broken.

- Additional masses can be given to gauginos, squarks, sleptons, Higgses to explain the mass splitting
  : It beaks SUSY but keeps the Λ^2 cancellation.
  (soft SUSY breaking).

- The SUSY-extended SM (with soft breaking terms) is a model free from the gauge hierarchy problem (fine-tuning problem) of the SM.

Minimal Supersymmetric SM (MSSM)

- Minimal : Minimal extension of fields and symmetry
  - Minimal gauge group
    : SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Minimal field contents
    : (SM fields + extra Higgs doublet) & Superpartners
  - Soft breaking terms
    : to break Supersymmetry
  - R-parity
    : to avoid fast proton-decay

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The only additions in the MSSM besides SUSY and its breaking terms

- Question :

  Assuming Supersymmetry at TeV-scale, would the MSSM be a Supersymmetric SM that can describe the TeV-scale physics adequately?

μ-problem of the MSSM

- MSSM superpotential :

$$W_{MSSM} = \lambda_E LH_2E^C + \lambda_D QH_2D^C + \lambda_U QH_1U^C + \mu \mathbf{H_1H_2}$$

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$$\downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow$$

[0] [0] [0] [1]

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$$[0] \qquad [0] \qquad [0] \qquad [1]$$

μ : the only dimensionful parameter (i.e., it has a scale) in SUSY-conserving sector in the MSSM

- Quadratic scalar potential :

  $V_{(2)} = \mu^{\mathbf{2}} (|H_{\mathbf{1}}{}^0|^2 + |H_2{}^0|^2)$ + (EW/TeV-scale SUSY-breaking terms)

  To have Higgs VEV of EW-scale, <u>μ should be also EW-scale</u> to avoid fine-tuning.

- Why SUSY-conserving parameter (μ) scale $\approx$ SUSY-breaking parameter (soft terms) scale?

  MSSM does not provide the answer. (the μ-problem : fine-tuning problem of MSSM)

  Kim,Nilles [PLB138 (1984) 150]

Other issues in the MSSM (cosmology related)

- To have a sufficient first-order EW phase transition for the Electroweak Baryogenesis (EWBG), m_h should be only slightly above the LEP limit and $m_{stop} < m_{top}$. (fine-tuning in the parameter space of MSSM)

- In the minimal Supergravity model, the parameter space that can reproduce the acceptable CDM relic density is becoming increasingly narrow when combined with the LEP constraints (Higgs mass, chargino mass). (fine-tuning in the parameter space of CMSSM)

- The issues in the MSSM suggest :

  Even if nature holds Supersymmetry at TeV-scale, the MSSM may not fully describe the TeV-scale physics.

What is next?

Model	SM	MSSM
Fine-tuning problem	gauge hierarchy problem	μ-problem
Cure	Supersymmetry	What (symmetry)?

- What (symmetry) would be cure of the fine-tuning in the MSSM?
- And what would be the naturally extended model of the MSSM that can suitably describe TeV-scale physics?

2. U(1)′-extended MSSM

- Consider a TeV-scale Abelian gauge symmetry, U(1)′, as a cure of the fine-tuning problem in the MSSM.

U(1)′-extended MSSM

- Gauge group
  : $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$
- Field contents
  : (SM fields + extra Higgs doublet + Z′ boson
  + Higgs singlet + Exotic fermions) & Superpartners
- Soft breaking terms
  : to break Supersymmetry
- R-parity
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- Introduction of the U(1)′ symmetry requires extension in the field contents.

  - Z′ boson : gauge boson of U(1)′
  - Higgs singlet : to break U(1)′ symmetry spontaneously
  - Exotic fermions : U(1)′ may need more fermions to cancel the anomaly

  & Superpartners of the above fields

- Specific U(1)′ breaking scalar potential and exotic field contents are model dependent. (We do not specify them here.)
- Examples of the specific Supersymmetric U(1)′ models :
  - Superstring-motivated model

    Cvetic,Demir,Espinosa,Everett,Langacker [PRD56 (1997) 2861]
  - E_6 GUT model

    Langacker,Wang [PRD58 (1998) 115010]
  - Multiple singlets model

    Erler,Langacker,Li [PRD66 (2002) 015002]

- U(1)′-extended MSSM superpotential :

$$W_{U(1)'\text{-MSSM}} = \lambda_E LH_2E^C + \lambda_D QH_2D^C + \lambda_U QH_1U^C$$

$$+ \mathbf{h_S\, SH_1H_2}$$

- μH_1H_2 is prohibited by the U(1)′ charge assignment and μ-term is replaced by the VEV of the Higgs singlet of TeV-scale.

  $\mu_{eff} = h_S \langle S\rangle$ (no μ-problem)

  (for example, $Q'(H_1) = Q'(H_2) = -1$, $Q'(S) = 2$)

- Instead of a discrete symmetry (of NMSSM), an Abelian gauge symmetry U(1)′ is introduced. → no domain wall

- The Higgs singlet S [charged under only U(1)′] is responsible to break the U(1)′ spontaneously at the EW/TeV-scale and also plays the role of μ_{eff}.

- It naturally predicts a <u>EW/TeV-scale Z′ gauge boson</u> :

$$M_{Z'} = g_{Z'} \left[Q'(H_1)^2 v_1^2 + Q'(H_2)^2 v_2^2 + Q'(S)^2 s^2\right]^{1/2}$$

$$\sim g_{Z'} Q'(S)\, s \sim O(EW/TeV)$$

(since $\mu_{eff} = h_S \langle S\rangle \sim O(EW)$) $\quad (\langle S\rangle \equiv s / 2^{1/2})$

Sources of U(1)′

- U(1)′-extended MSSM is a natural extension of the MSSM since, besides the bottom-up reasons (μ-problem solution), many new physics models predict extra U(1) symmetries or Gauge bosons :
  - Grand Unified Theory
  - Extra dimension
  - Superstring
  - Dynamical EW symmetry breaking
  - Little Higgs

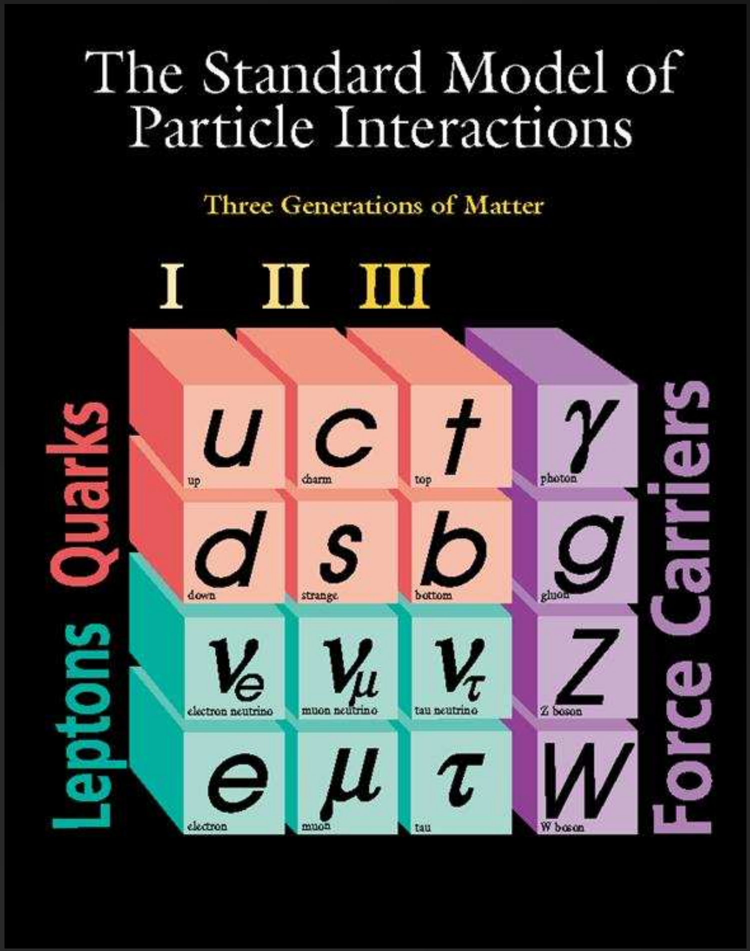
Extended/Modified particle spectrum

- (1) Gauge boson sector (Z′)
- (2) Higgs sector (S)
- (3) Neutralino sector (Z′-ino, singlino)
- (4) Neutrino sector (U(1)′ charged ν_R)

We will discuss the phenomenology of these sectors with specific examples later.

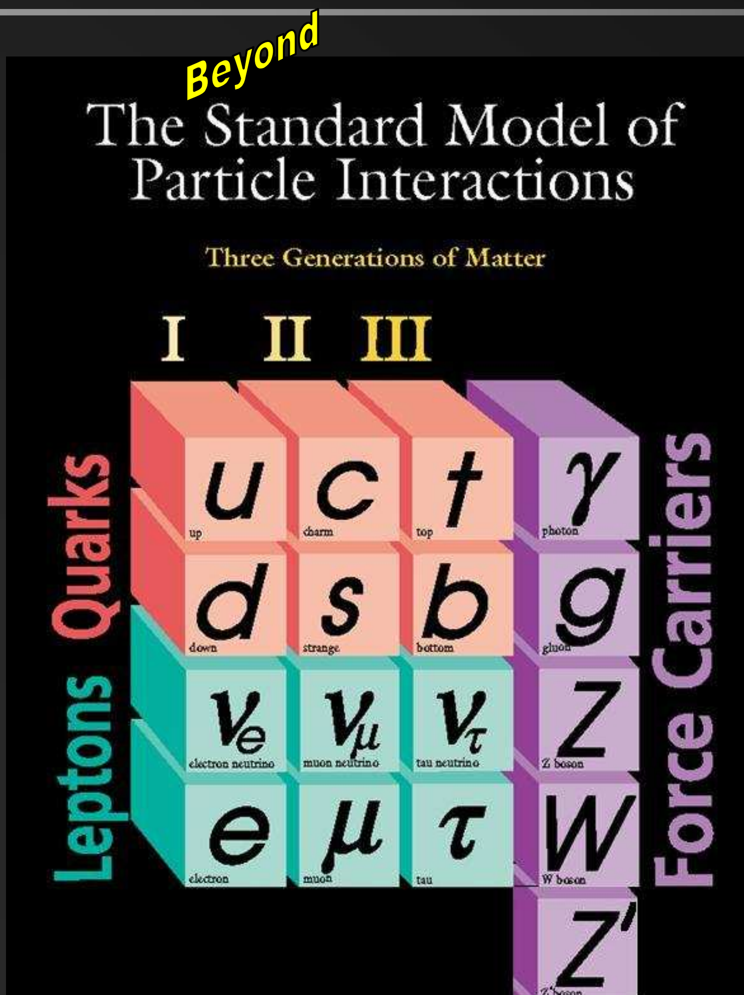
3. TeV-scale U(1)’ gauge boson

New force carrier



- U(1)′ is a new force and it needs a new force carrier (Z′).
- The U(1)′-extended MSSM predicts the mass of Z′ to be EW/TeV-scale.

New force carrier



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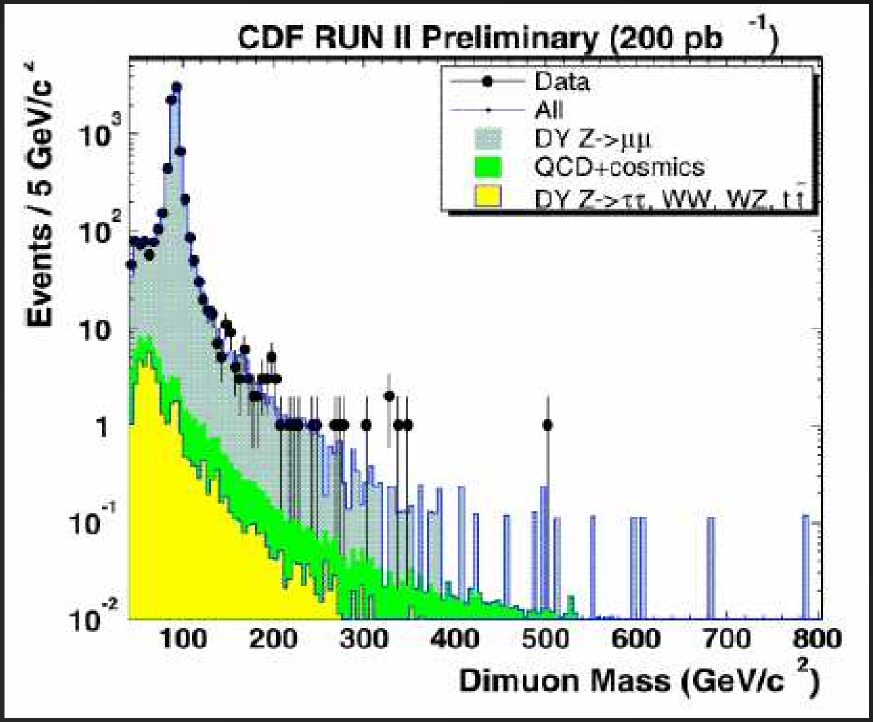
Resonance by Z′



- The direct detection of Z′ can be achieved by observation of the resonance (the most distinctive feature from the MSSM) in difermion (dilepton or dijet) channels.

CDF Run2 Preliminary [Northwestern Workshop on Z′s (Nov ‘04)]

CDF Z′ mass limits from dilepton search

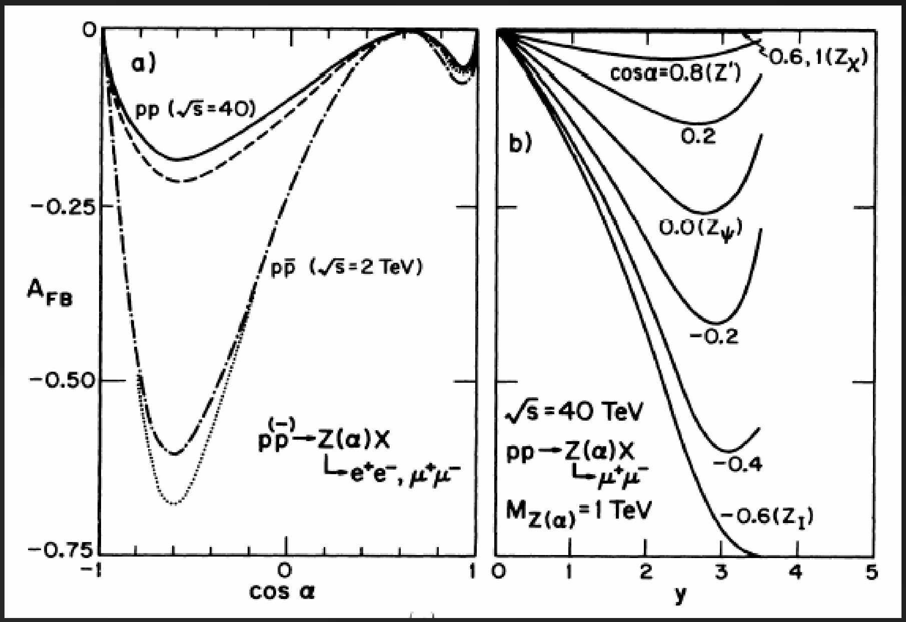
E_6 Mass Limit at 95%C.L (GeV/c^2)

Model	ee	$\mu\mu$	$\ell^+\ell^-$
Z'_{SM}	750	735	815
Z'_{ψ}	635	600	690
Z'_{χ}	620	585	670
Z'_{η}	655	640	715
Z'_{I}	575	540	610

CDF Run2 Preliminary [Northwestern Workshop on Z′s (Nov '04)]

- The current limits of Z′ mass are (600 ~ 800) GeV depending on models.
- Resonance is one of the cleanest signal.
- The LHC reach of Z′ would be 2 TeV at day 1; it can search Z′ up to 5 TeV.

Distinguishing models



- Forward-Backward asymmetry (A_{FB}) contains information of the charge assignments.
- It is very useful in identifying gauge bosons (e.g., among E_6 models).

Barger,Deshpande,Rosner,Whisnant [PRD35 (1987) 2893]

A_{FB} in p-p (p-pbar) → Z′ → l^+l^- versus E_6 mixing angle and rapidity

Other potential sources of resonance (Z'-like signals)

- Observing the resonance does not necessarily mean the existence of additional U(1) symmetry.
  - Part of non-Abelian gauge symmetry such as the 3rd component of $SU(2)_R$
  - Kaluza-Klein excitations in extra dimension
  - String resonance

- Identifying the source of the resonance would be important.

Z-Z′ mixing

- $Z_1 = Z_{SM} \cos\delta + Z' \sin\delta$
- $Z_2 = -Z_{SM} \sin\delta + Z' \cos\delta$
- $\tan^2\delta = (M_{Z_{SM}}^2 - M_{Z_1}^2)/(M_{Z_2}^2 - M_{Z_{SM}}^2)$: mix. angle of Z-Z′

- LEP result (precision measurement of coupling constants at the Z-pole) : $|\delta| < (\text{a few}) \times 10^{-3}$

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- LEP result (precision measurement of coupling constants at the Z-pole) : $|\delta| < (\text{a few}) \times 10^{-3}$
- Why so small mixing?

  → This is a natural value for sufficiently heavy Z′

  (about current experimental limit of 600 ~ 800 GeV or heavier)

4. Implications of U(1)’-extended MSSM

(1) Higgs sector
(2) Neutrino sector
(3) Neutralino sector
(4) Gauge boson sector [CP & FCNC]

(1) Higgs sector

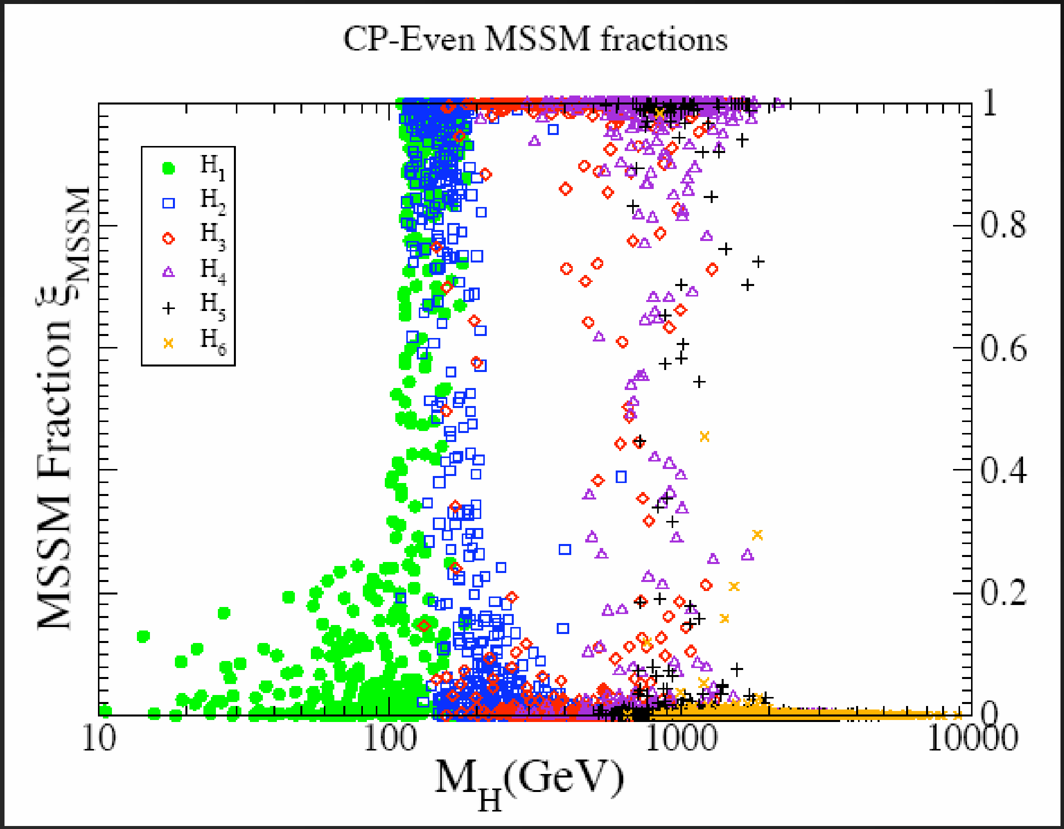
- Higgs singlet (S) is added to break U(1)′ symmetry spontaneously.
- Higgs singlet does not interact with other MSSM particles except Higgs doublets ($W = \ldots + h_S\, S H_1 H_2$).
- The mixing of Higgs doublet and singlet under U(1)′ symmetry modifies the masses and couplings of the physical states of Higgs.
  - (ex-i) Theoretical upper bound on the Higgs mass
  - (ex-ii) LEP2 lower bound on the Higgs mass

(ex-i) Theoretical upper bound on the Higgs mass

- The upper bound on the lightest Higgs mass in Supersymmetric models is determined by the gauge couplings.
- With an additional gauge symmetry, U(1)′, the Higgs mass bound increases from that of the MSSM.
  - The lightest Higgs mass $\lesssim$ 130 GeV [MSSM]
  - The lightest Higgs mass $\lesssim$ 170 GeV [U(1)′-MSSM]

$$
\begin{aligned}
M_h^2 \quad &\leq \quad h^2 v^2 + (M_Z^2 - h^2 v^2)\cos^2 2\beta \\
&+ \quad \underline{2 g_{Z'}^2 v^2 (Q_{H_2}\cos^2\beta + Q_{H_1}\sin^2\beta)^2} \\
&+ \quad \frac{3}{4}\frac{m_t^4}{v^2\pi^2}\log\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}.
\end{aligned}
$$

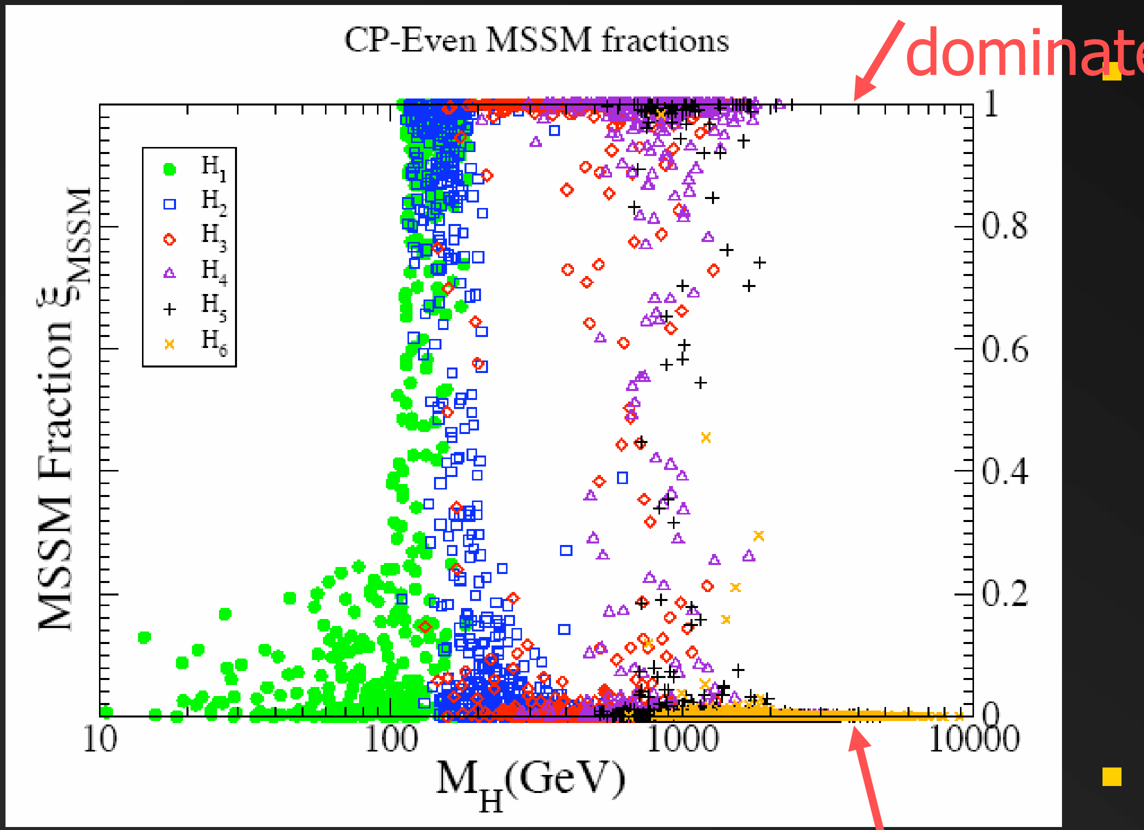
(ex-ii) LEP2 lower bound on the Higgs mass



Han,Langacker,McElrath [PRD70 (2004) 115006]

- LEP2 constraint on the mass of the <u>lightest Higgs (green dots)</u> depends on the mixing status of the doublet and singlet (smaller ZZH for more singlet ratio).
- The SM-like lightest Higgs mass (m_h > 114 GeV) does not apply.

(ex-ii) LEP2 lower bound on the Higgs mass



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Higgs sector		
	MSSM	U(1)′-extended MSSM
Theoretical upper bound	$m_h \lesssim 130$ GeV	$m_h \lesssim 170$ GeV
LEP2 lower bound	$m_h > 114$ GeV	$m_h \sim O(10)$ GeV is possible
Reason	$SU(2)_L$ doublet	Mixture of $SU(2)_L$ doublet and singlet under additional gauge

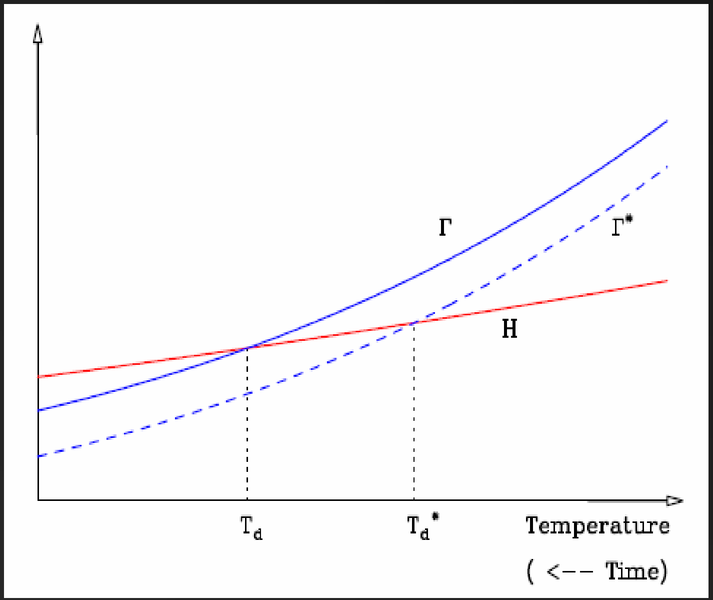
(2) Neutrino sector

- If ν_R carries a charge of the TeV-scale U(1)′ symmetry,
  $$m_{\nu_R} \lesssim O(\text{TeV}).$$
- The Majorana mass of the ν_R is not large enough for the ordinary seesaw mechanism.

  (Large mass is still possible if its charge is 0.)

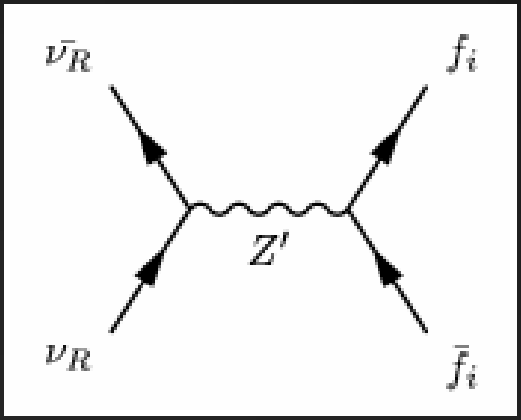
- We assume 3 Dirac neutrinos with negligible masses, not specifying a mechanism (e.g., extra dim) for light mass.
  - (ex-i) Big Bang Nucleosynthesis (BBN) constraint on Z′
  - (ex-ii) Neutrinoless double beta decay ($0\nu\beta\beta$)

(ex-i) Big Bang Nucleosynthesis (BBN) constraint on Z′



$\Gamma(T)$: interaction rate of particle A
$H(T)$: cosmological expansion rate

- For $\Gamma > H$, particle A is in equilibrium.
  For $\Gamma < H$, particle A is decoupled.
- Decoupling temperature (T_d) of A, where $\Gamma(T_d) = H(T_d)$, carries information of interaction strength of A.



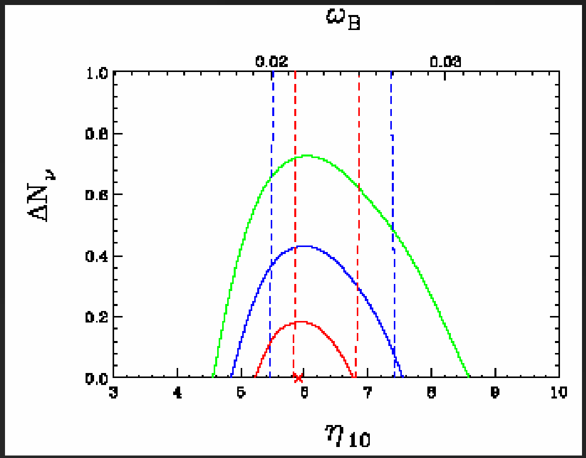
$[G_{SW} \propto g_{Z'}^2/M_{Z'}^2] \ll [G_W \propto g_Z^2/M_Z^2]$

for ν_R for ν_L

- ν_R is a particle with small interaction strength compared to that of ν_L since it couples only to (very heavy) Z'.

- Additional relativistic d.o.f. (ν_R) predicts larger primordial ^{4}He abundance (by increasing expansion rate) from BBN.
- Attribute this as the source of the uncertainty in the ^{4}He abundance data (ΔY) to constrain Z′ property.
- Larger mass of gauge boson (larger $M_{Z'}$)
  → smaller Γ of ν_R
  → earlier decoupling (from BBN era)
  → smaller ΔY
  Steigman,Olive,Schramm [PRL43 (1979) 239]

- A discrepancy in ^{4}He abundance (Y) data in terms of the effective L.H. neutrino number ($N_\nu \propto Y$) :

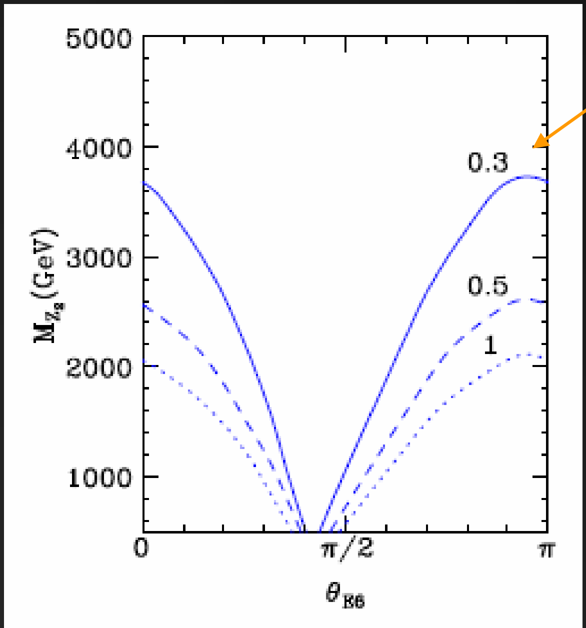


From BBN(+WMAP) data,
$\Delta N_\nu \leq 0.3$ at 2σ level
(with $N_\nu \geq 3$ condition).

Barger,Kneller,HL,Marfatia,Steigman [PLB566 (2003) 8]

- ΔN_ν value depends on the data and the analysis group but the typical range is $\Delta N_\nu \leq (0.3 \sim 1)$.

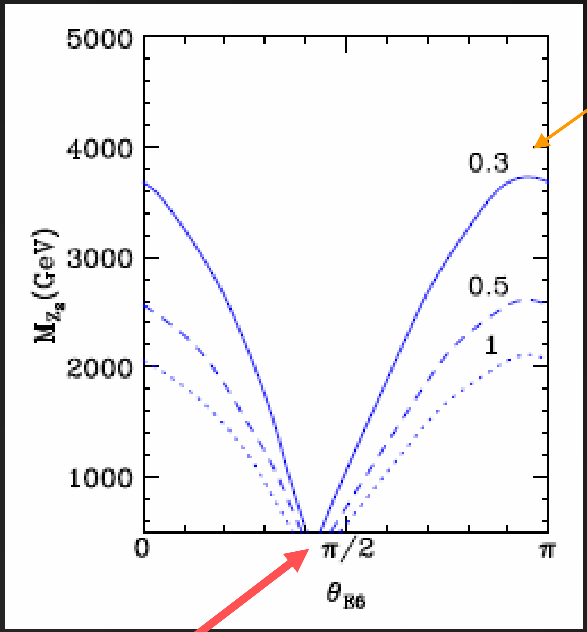
$M_{Z'}$ lower bound



for a given ΔN_ν (effective neutrino number) $\propto \Delta Y$

Barger,Langacker,HL [PRD67 (2003) 075009]

$M_{Z'}$ lower bound



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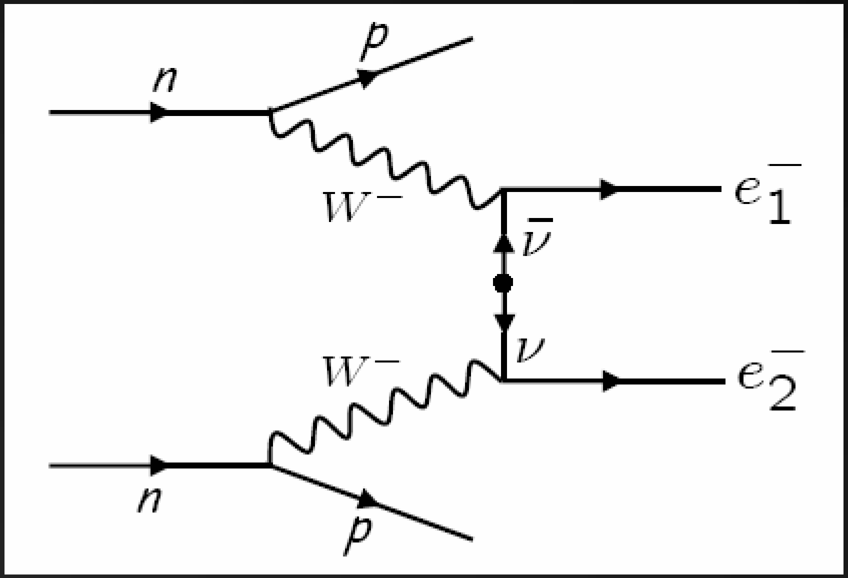
Barger, Langacker, HL [PRD67 (2003) 075009]

- At θ_{E6} (mixing angle of 2 U(1)'s in E_6 model) = 0.42 π, <u>$Q'(\nu_R) = 0$</u> (ν_R does not couple to Z').
- BBN gives **the most stringent constraint** on Z' mass (mostly, $M_{Z'} \sim$ multi-TeV).

(ex-ii) Neutrinoless double beta decay ($0\nu\beta\beta$)

- $0\nu\beta\beta$ is not generally expected to be observed ($0\nu\beta\beta$ is possible for Majorana neutrinos).

- Still possible if $Q'(\nu_R) = 0$.



Neutrino sector		
	MSSM	U(1)′-extended MSSM
ΔN_ν from BBN	No significant contribution to N_ν from superparticles	Discrepancy may be due to super-weakly interacting ν_R
$0\nu\beta\beta$	(Usually) expected	Not expected [still possible]
Reason	Seesaw mechanism	U(1)′ charged ν_R forms Dirac and couples to only (heavy) Z′

(3) Neutralino sector

- Singlino and Z′-ino are added as the Supersymmetric partners of Higgs singlet and Z′ boson.

- Neutralino sector is extended to 6-components [MSSM: 4, NMSSM: 5] with modified masses and couplings.

- Neutralino mass matrix in the basis of
  χ^0 = {Bino, Wino, Higgsino$_1$, Higgsino$_2$, Singlino, Z′-ino}:

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\ 0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\ -g_1 v_1/2 & g_2 v_1/2 & 0 & -h_s s/\sqrt{2} & -h_s v_2/\sqrt{2} & g_{Z'} Q'(H_1^0) v_1 \\ g_1 v_2/2 & -g_2 v_2/2 & -h_s s/\sqrt{2} & 0 & -h_s v_1/\sqrt{2} & g_{Z'} Q'(H_2^0) v_2 \\ 0 & 0 & -h_s v_2/\sqrt{2} & -h_s v_1/\sqrt{2} & 0 & g_{Z'} Q'(S) s \\ 0 & 0 & g_{Z'} Q'(H_1^0) v_1 & g_{Z'} Q'(H_2^0) v_2 & g_{Z'} Q'(S) s & M_{1'} \end{pmatrix}$$

- Neutralino mass matrix in the basis of
  χ^0 = {Bino, Wino, Higgsino$_1$, Higgsino$_2$, Singlino, Z′-ino}:

MSSM NMSSM (with κ=0) U(1)′

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- Neutralinos are important in many physics including
  - (ex-i) Cold dark matter (CDM) relic density
  - (ex-ii) Muon anomalous magnetic moment $(g\text{-}2)_\mu$

- MSSM can already reproduce acceptable CDM relic density and measured deviation of $(g\text{-}2)_\mu$.
- U(1)′-extended MSSM (with more parameters) can easily reproduce the similar results as the MSSM (without the μ-problem).

- We consider a variant of U(1)′-extended MSSM [multiple singlets U(1)′ model] which has more restrictions on parameter space and see if it still has solutions for these two experimental results.

A Variant : Multiple singlets U(1)′ model

- 3 more Higgs singlets (S_1, S_2, S_3) are added.
- Superpotential for the Higgs sector :

Erler,Langacker,Li [PRD66 (2002) 015002]

$$W_{S\text{-model}} = h_S\, S H_1 H_2 + \lambda_S\, S_1 S_2 S_3$$

- It can explain very heavy Z′ (multi-TeV) easily while keeping μ_{eff} at EW scale.

$$M_{Z'} = g_{Z'} [Q'(H_1)^2 v_1^2 + Q'(H_2)^2 v_2^2 + Q'(S)^2 s^2 + \textstyle\sum_{i=1\sim3} Q'(S_i)^2 s_i^2]^{1/2}$$

$$\mu_{eff} = h_S \langle S \rangle$$

additional contributions from $\langle S_{1,2,3} \rangle$

- Interesting features of the multiple singlets model :
  - Small tanβ(= 1~3) is required to be consistent with the EW symmetry breaking. (→ restricted parameter space)
  - Provides acceptable level of EWBG.

    Kang,Langacker,Li,Liu [hep-ph/0402086]
  - Typically, heavy masses for extra Singlino$_{1,2,3}$ limit works well to generate realistic values for Higgs doublets and singlet VEVs. → We take this limit for calculation.

(ex-i) Cold Dark Matter (CDM) relic density

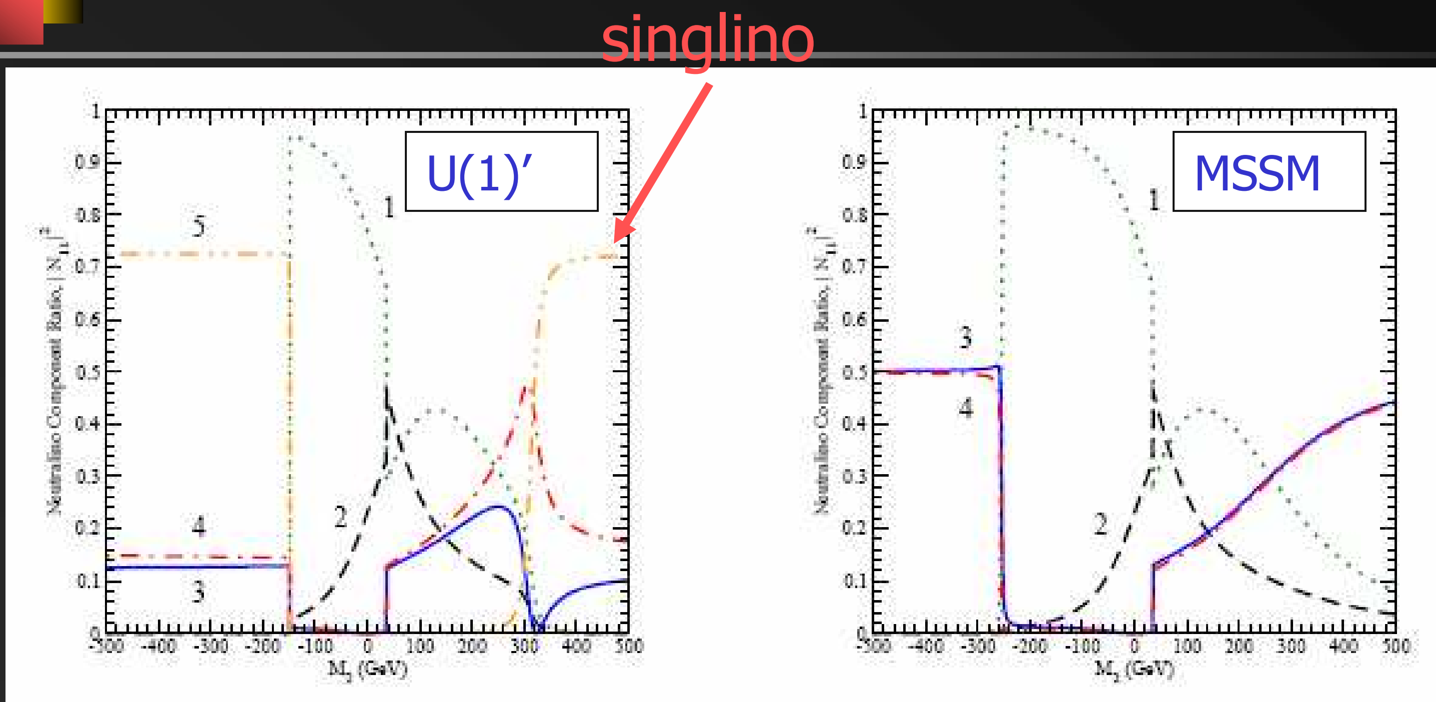
- WMAP precise measurement of CDM relic density :
  $0.09 < \Omega_{CDM}h^2 < 0.15$ (3σ allowed range)
  WMAP collaboration [APJ Sup148 (2003) 175]
  Barger,HL,Marfatia [PLB565 (2003) 33]

- The lightest neutralino (χ^0_1) is a strong candidate for the CDM, and it should reproduce the measured $\Omega_{CDM}h^2$.

- The lightest neutralino is often singlino-dominated and its mass bound is smaller than that of MSSM.
  (e.g., mass of $\chi^0_1 < 100$ GeV for heavy Z'-ino)

- Z'-pole itself is too heavy to be a relevant annihilation channel.

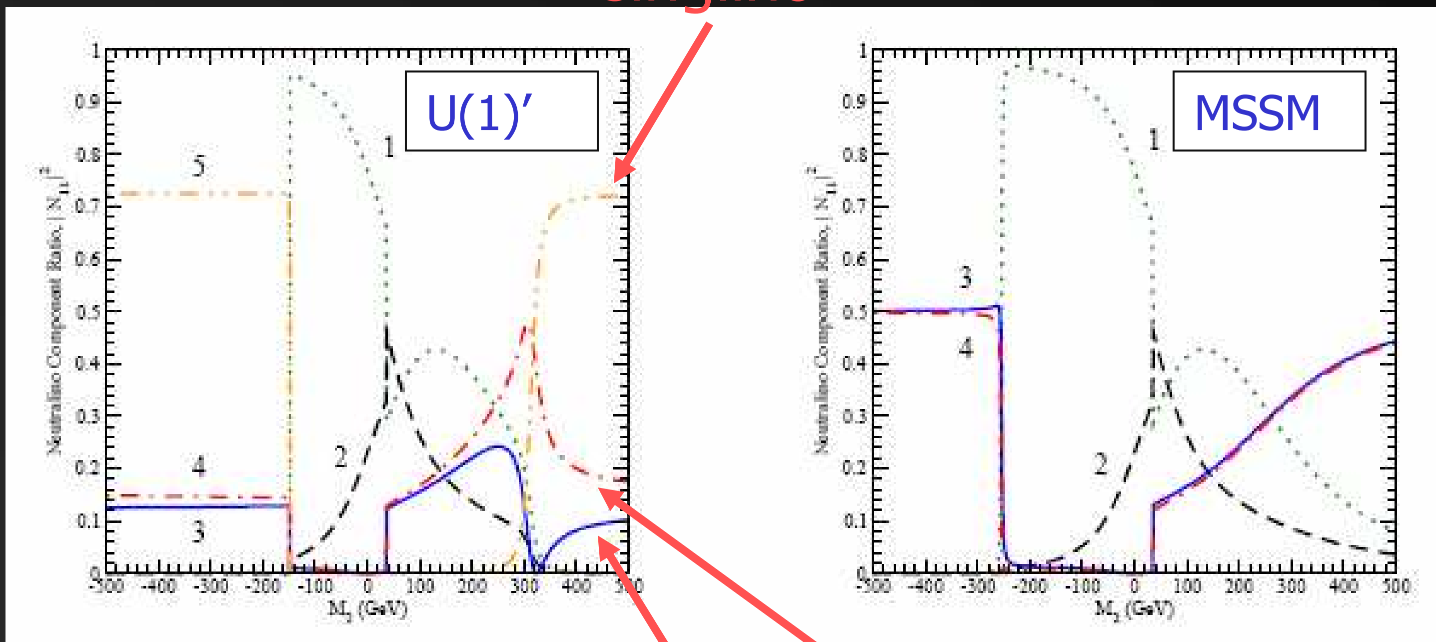
- But, distinctive channels [from MSSM] can still arise because of the modified mass and coupling of the χ^0_1 : e.g., the Z-χ^0_1-χ^0_1 coupling is enhanced even for small $\tan\beta$.



χ^0_1 composition

- For $\tan\beta \approx 1$,
  Z-χ^0_1-χ^0_1 coupling $\propto (|N_{13}|^2 - |N_{14}|^2)$
  $\sim$ negligible [in MSSM]
  $\sim$ sizable [in U(1)′-MSSM]

singlino



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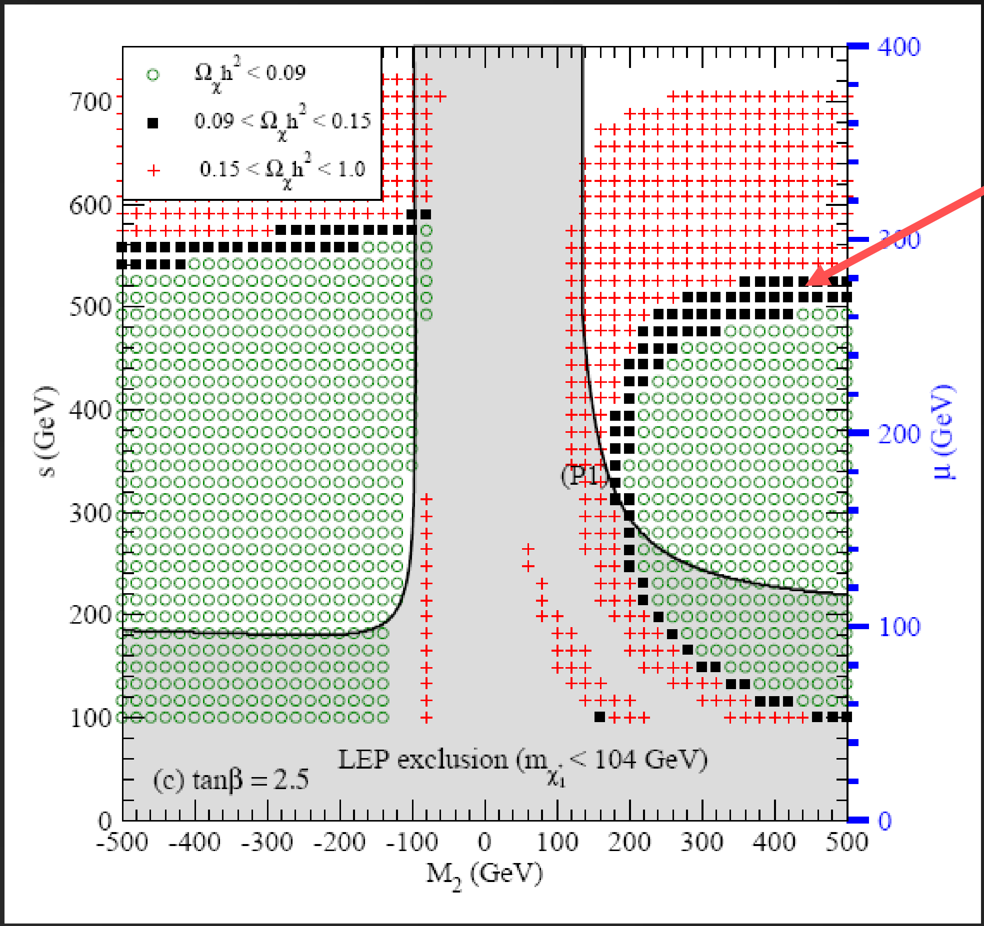


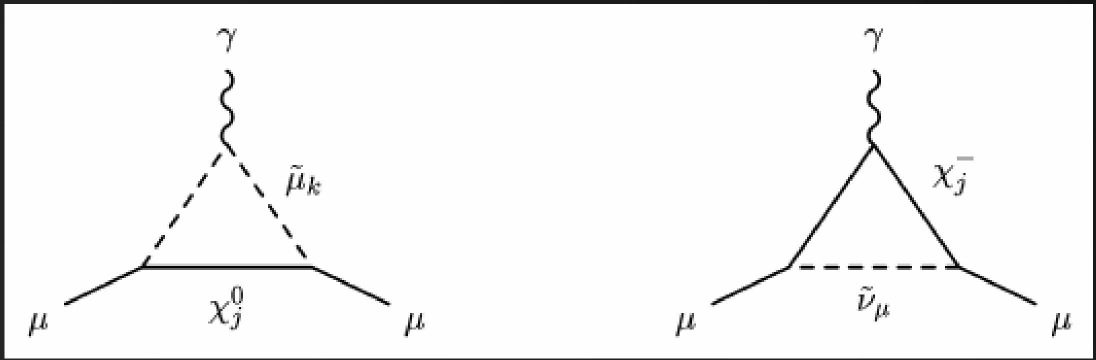
- The acceptable CDM relic density <u>$(0.09 < \Omega_{CDM}h^2 < 0.15)$</u> is reproduced even with only Z-pole channel [opening of a new channel].

Barger,Kao,Langacker,HL PLB600 (2004) 104]

(ex-ii) Muon anomalous magnetic moment $(g\text{-}2)_\mu$

- $(g\text{-}2)_\mu$ is one of the most precisely measured quantities.
- 2.4σ deviation from SM prediction (0.9σ if hadronic information is from indirect hadronic τ decay) was found by BNL experiment (E821).
- New physics models are constrained by the deviation:
  - In MSSM, sign(μ) > 0, upper limits on slepton masses
  - Compactification scale in an extra dimension
  - Z′ mass in U(1)′ or GUT models (Collider limit of 600 ~ 800 GeV is too heavy to reproduce the deviation when only Z′-loop is considered)

- The same Supersymmetric contributions to $(g\text{-}2)_\mu$ but with an extended neutralino sector exist.



- The $\mu - \tilde{\mu}_k - \chi_j^0$ chiral couplings (j = 1~6) :

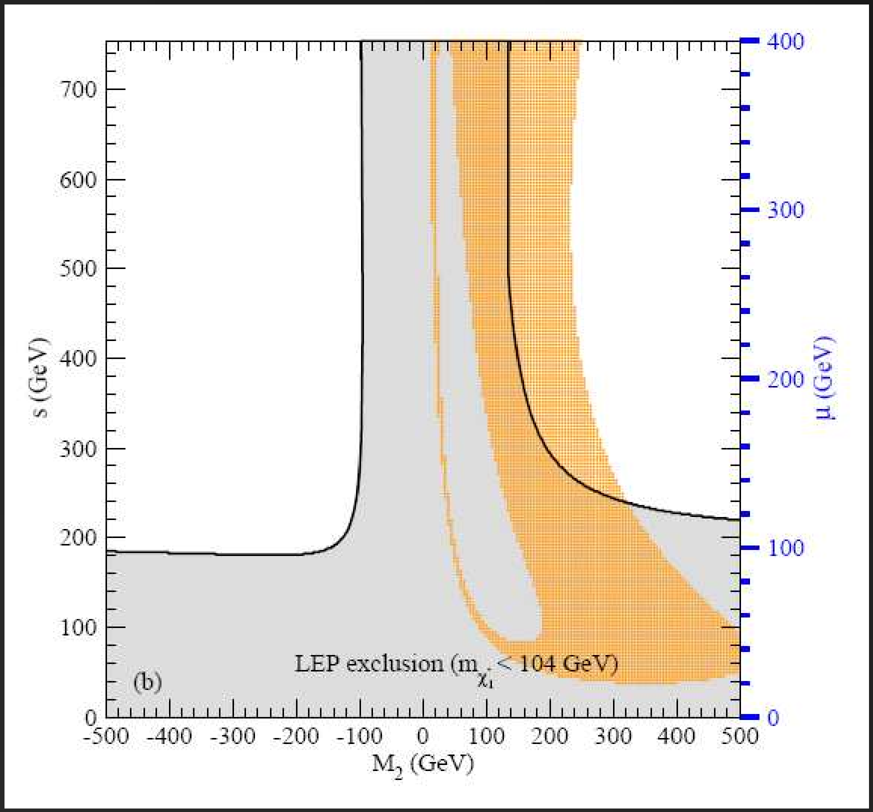
$$
\begin{aligned}
L_{jk} &= \frac{1}{\sqrt{2}}\left(g_1 Y_{\mu_L} N_{1j}^* - g_2 N_{2j}^* + \underline{g_{Z'} Q'(\mu_L) N_{6j}^*}\right) D_{1k} + \frac{\sqrt{2}m_\mu}{v_1} N_{3j}^* D_{2k} \\
R_{jk} &= \frac{1}{\sqrt{2}}\left(g_1 Y_{\mu_R} N_{1j} + \underline{g_{Z'} Q'(\mu_R) N_{6j}}\right) D_{2k} + \frac{\sqrt{2}m_\mu}{v_1} N_{3j} D_{1k}.
\end{aligned}
$$

- The Supersymmetric contribution to $(g-2)_\mu$ in the limit of degenerate Supersymmetric masses :

$$\Delta a_\mu(\mathrm{SUSY}) \sim 13 \times 10^{-10} \frac{\tan\beta \ \mathrm{sign}(\mu)}{(M_{\mathrm{SUSY}}/100 \ \mathrm{GeV})^2}$$

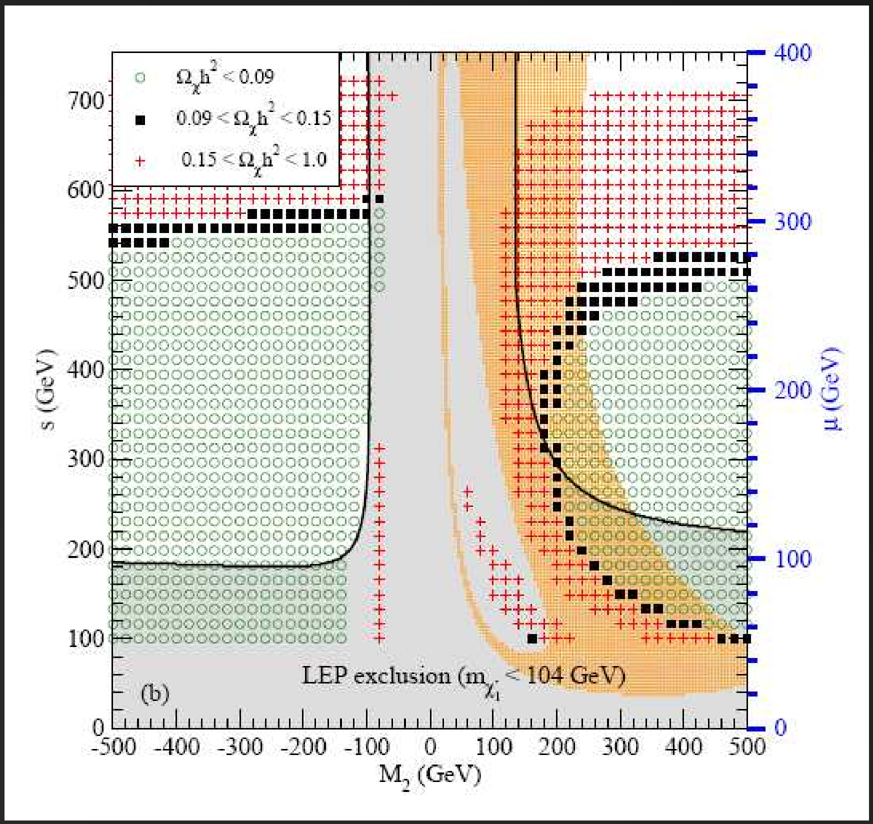
- The chargino and neutralino loop contributions are proportional to $\tan\beta$.

- Since $\tan\beta$ is small (= 1~3) in the multiple singlets U(1)′ model, it is not clear if it can explain the $(g-2)_\mu$ deviation.



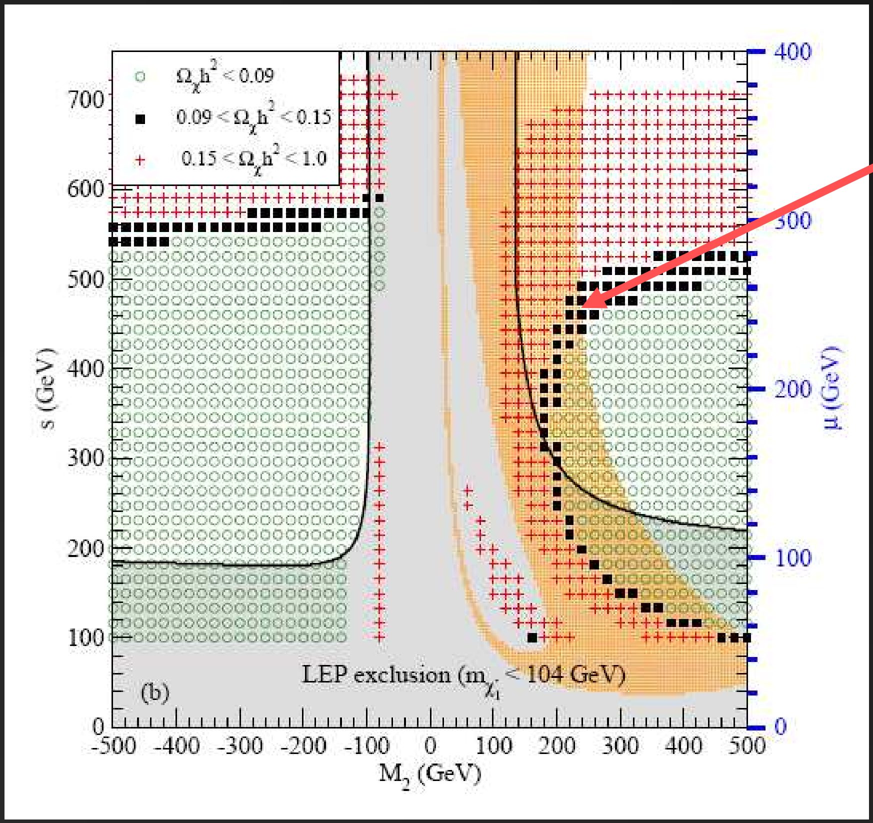
- The solutions exist that explain $(g-2)_\mu$ even with a small $\tan\beta$ (if mass of smuon < 180 GeV).
- The solution space is larger than MSSM.

Barger,Kao,Langacker,HL [hep-ph/0412136]



- **Common solutions** exist that explain $(g\text{-}2)_\mu$ and WMAP CDM relic density simultaneously.

Barger,Kao,Langacker,HL [hep-ph/0412136]



- **Common solutions** exist that explain $(g-2)_\mu$ and WMAP CDM relic density simultaneously.

Barger,Kao,Langacker,HL [hep-ph/0412136]

Neutralino sector		
	MSSM	multiple singlets U(1)′
LSP	typically Bino-dominated	typically Singlino-dominated
CDM relic density	For tan$\beta \approx 1$, Z-pole is irrelevant.	For tan$\beta \approx 1$, even Z-pole alone can reproduce.
2.4σ of $(g-2)_\mu$	Can explain	Can explain even with small tanβ and constrains smuon mass < 180 GeV.
Reason	4 component neutralino	6 component (singlino and Z′-ino) neutralino

(4) Gauge boson sector [with CP & FCNC]

- In U(1)′-extended models, extra sources of the CP phase exist due to the Higgs singlet in superpotential and soft term.

  Demir,Everett [PRD69 (2004) 15008]

- Additional CP phase and Flavor Changing Neutral Current (FCNC) are possible if Z′ has a family non-universal coupling (allowed in certain types of the String-motivated models).

  Langacker,Plumacher [PRD62 (2000) 13006]

(Ex) Left-handed d-type quark $U(1)'$ coupling matrix

$$\begin{aligned}\mathcal{L} &= -g_{Z'} Z'_\mu \left(\bar{d}_L^{\text{int}} \gamma_\mu \epsilon_{d_L} d_L^{\text{int}}\right) \\ &= -g_{Z'} Z'_\mu \left(\bar{d}_L \gamma_\mu B^L d_L\right)\end{aligned}$$

- $U(1)'$ coupling matrix in interaction eigenstate (d_L^{int}):

$$\epsilon_{d_L} = Q_{d_L} \begin{array}{cc} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\delta \end{pmatrix} & \begin{array}{c} d \\ s \\ b \end{array} \end{array}$$

- $U(1)'$ coupling matrix in mass eigenstate ($d_L = V_{d_L} d_L^{\text{int}}$):

$$\begin{aligned}B^L &\equiv V_{d_L} \epsilon_{d_L} V_{d_L}^\dagger = Q_{d_L} V_{d_L} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1+\delta \end{pmatrix} V_{d_L}^\dagger \\ &= \left[\begin{array}{ll} Q_{d_L} \mathbf{1}_{3\times 3} & (\text{if } \delta = 0) \\ \text{general } 3\times 3 \text{ matrix} & (\text{if } \delta \neq 0) \end{array} \right.\end{aligned}$$

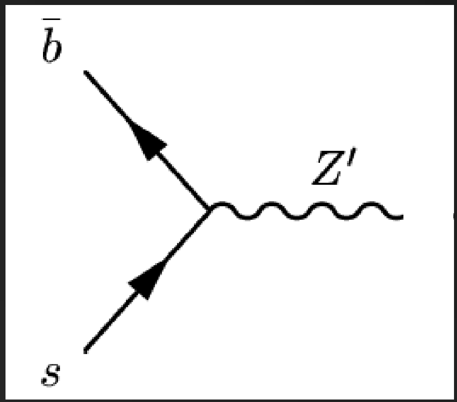
B^L has off-diagonal terms with phases originated from V_{d_L}. (And similarly for u-type quark and/or Right-handed coupling.)

The usual CKM matrix is given by $V_{CKM} = V_{u_L} V_{d_L}^\dagger$.

non-universal but still no FCNC in interaction eigenstate

induced FCNC and phases in mass eigenstate

- FCNC by Z′ is suppressed by its large mass, but it is tree-level while SM FCNC are all loop-suppressed.
  - (ex-i) Rare B-decays ($B_d \rightarrow \pi K$, $B_d \rightarrow \phi K_S$)
  - (ex-ii) EW Precision Test ($A_{FB}^{0,b}$)



(ex-i) Rare B-decays ($B_d \rightarrow \pi K$, $B_d \rightarrow \phi K_S$)

- [$B \rightarrow \pi K$ puzzle]

  $B \rightarrow \pi K$ branching ratios showed 2.4σ [early 2004] deviation from the SM (by separate BaBar, Belle, CLEO data). Data suggests NP effect in EW Penguin sector.

- [$B \rightarrow \phi K_S$ CP anomaly]

  $B \rightarrow \phi K_S$ is NP-sensitive since SM contribution is only loop-order. Belle data showed its CP asymmetry ($S_{\phi K}$) deviated by 3.5σ [early 2004] from the SM.

- *The deviations are reduced in the recent data, but still show the discrepancies (~2σ levels).*

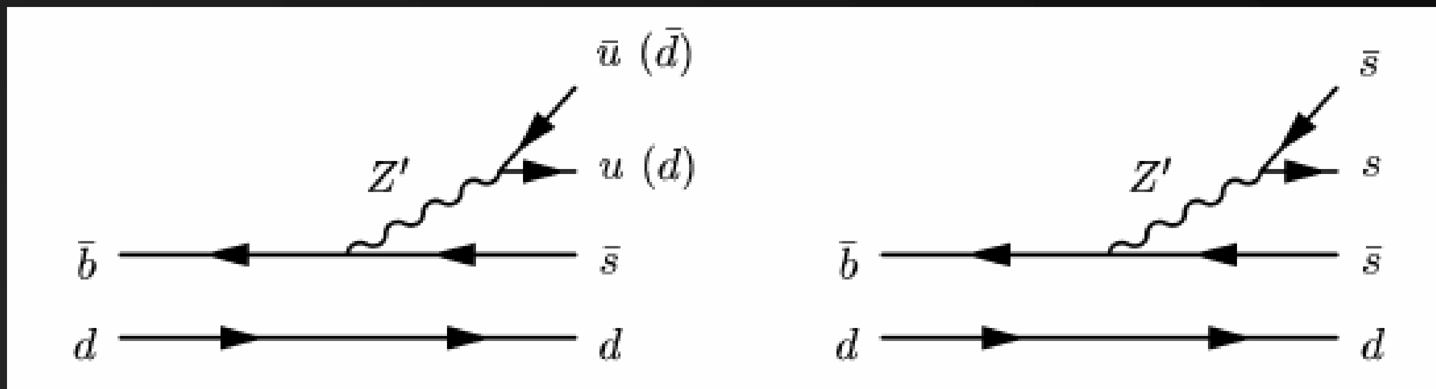
- Z′ contribution simplified (to reduce parameters) :
  (1) only to EW Penguin sector (suggested by B → πK)
  (2) flavor-changing only for left-handed coupling

- Effective Hamiltonian for b→s flavor-changing Z′ is

$$\Delta\mathcal{H} = \sqrt{2} G_F \left(\frac{g_{Z'} M_Z}{g_Z M_{Z'}}\right)^2 B_{sb}^{L*} (\bar{b}s)_{V-A} \sum_q \left(B_{qq}^L (\bar{q}q)_{V-A} + B_{qq}^R (\bar{q}q)_{V+A}\right) + \text{h.c.}$$

- Contributions to the EW Penguin coefficients (c_9, c_7) are

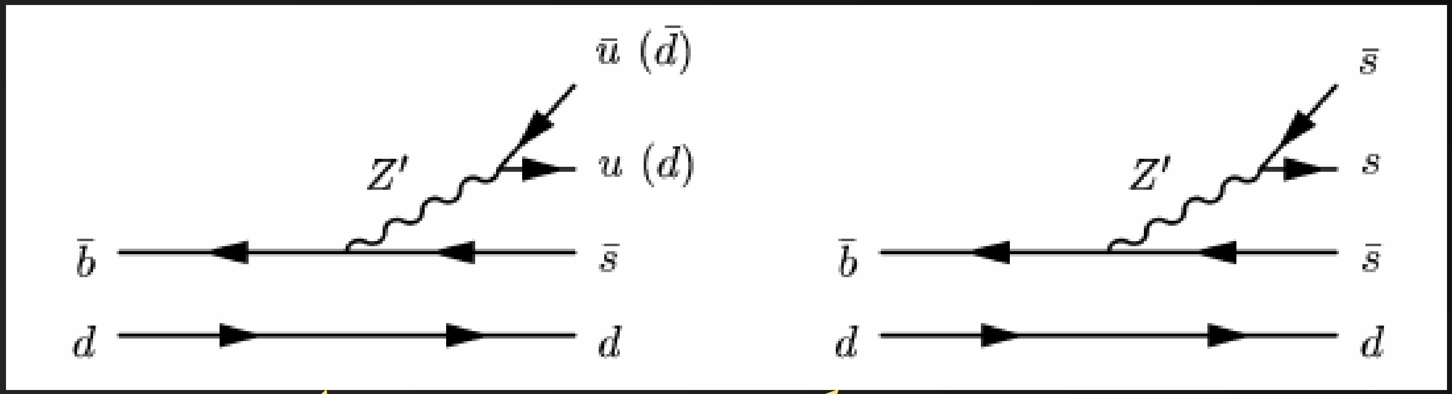
$$\Delta c_{9(7)} = \frac{4}{V_{tb}^* V_{ts}} \left(\frac{g_{Z'} M_Z}{g_Z M_{Z'}}\right)^2 B_{sb}^{L*} B_{dd}^{L(R)}$$



Barger,Chiang,Langacker,HL [PLB598 (2004) 218]

Barger,Chiang,Langacker,HL [PLB580 (2004) 186]

- Both B → πK and B → ϕK_S anomalies can be successfully explained with a TeV-scale flavor-changing Z′ with **common parameter values** without conflicts with related experiments such as B → $\eta' K_S$ and Mercury EDM (Electric Dipole Moment).

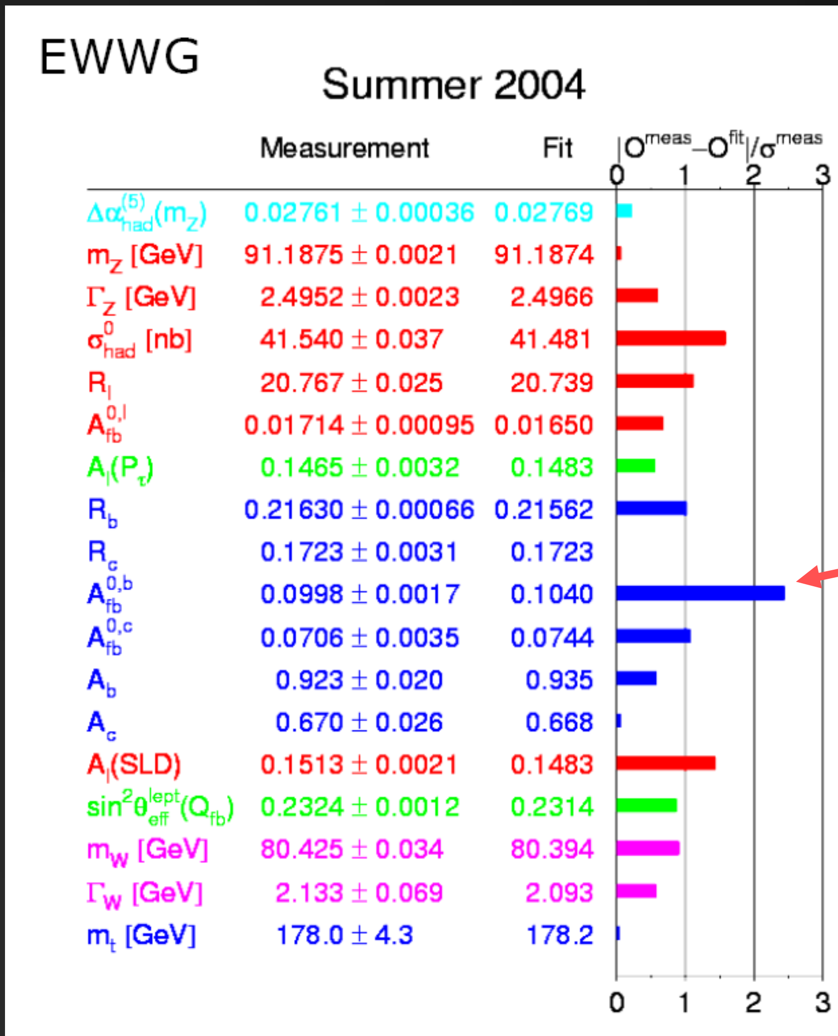


Barger,Chiang,Langacker,HL [PLB598 (2004) 218]

Barger,Chiang,Langacker,HL [PLB580 (2004) 186]

- Both $B \to \pi K$ and $B \to \phi K_S$ anomalies can be successfully explained with a TeV-scale flavor-changing Z′ with **common parameter values** without conflicts with related experiments such as $B \to \eta' K_S$ and Mercury EDM (Electric Dipole Moment).

(ex-ii) EW Precision Test



- EW precision data agree well with SM.
- The largest discrepancy is the 2.5σ of $A_{FB}^{0,b}$.

Riemann [Northwestern Workshop on Z's (Nov '04)]

- The 2.5σ discrepancy of $A_{FB}^{0,b}$ may be due to the NP affecting preferentially the 3rd generation with sizable effect.

- The tree-level FCNC by Z′ may be the source of the $A_{FB}^{0,b}$ discrepancy.

- The TeV-scale Z′ with different 3rd family coupling can provide a better fit for the EW precision data.

  Erler,Langacker [PRL84 (2000) 212]

Gauge Boson sector [with CP & FCNC]		
	MSSM	U(1)′-extended MSSM
Rare B decays	Some Supersymmetric solutions exist.	Supersymmetric solutions + additional flavor-changing Z′ solutions exist.
EWPT		$A_{FB}^{0,b}$ may be due to flavor-changing Z′.
Reason	FCNC by loops of superparticles	Z′-mediated FCNC can be sizable at tree-level.

5. Summary

- SM was extended to the Supersymmetric model to resolve the fine-tuning problem (gauge hierarchy problem), but its minimal model (MSSM) has its own fine-tuning problem (μ-problem) related to Higgs mixing parameter.
- U(1)′-extended MSSM may be a natural extension of the MSSM : It solves the μ-problem and is rationalized by many new physics models that predict additional U(1) symmetries. [GUT, Extra dim, String, Strong dynamics, Little Higgs]

- Solution of μ-problem implies EW/TeV-scale for the U(1)′ gauge boson Z′. (LHC can search up to 5 TeV.)
- Particle spectrums are extended in the U(1)′-extended MSSM [Gauge boson, Higgs, Neutralino, Neutrino] and properties of “important” particles [light Higgs, lightest neutralino (LSP)] may change.

- The extended/modified particle spectrum serve as rich source of phenomenology :
  - High-E collider [Z′, Higgs]
  - Non-collider [$0\nu\beta\beta$, $(g-2)_\mu$]
  - Astro/Cosmology [BBN, CDM relic density]
  - Rare decays [$B_d \to \pi K$, $B_d \to \phi K_S$]
  - EWPT [$A_{FB}^{0,b}$]

- A crucial check of the model is to observe a TeV-scale resonance and to identify it using collider and the other data.

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